Cullen Sarles, Alexandria Byrd, Ron Duarte, Dr. Karl von Ellenrieder, Daniel Gorelik, Mark Groden, Robert Gutzwiller, Davis Knox, Greg Koch, Jeremy Payne, John Reeder, Phillip Verbancsics, Virginia Wang, Dr. Robert A. Brizzolara (ONR)

UV Sentry: A Collaborative Approach to Creating a Collaborative System

ABSTRACT

This paper will describe the processes and results of a pilot project conducted during FY11 as part of the Office of Naval Research's Center for Innovation in Naval Technology (CINT). The project goals were to assist in developing a networked, cross-organizational approach to establishing future requirements for multi-unmanned vehicle autonomy; and to identify technology gaps, challenges, and potential innovative approaches for technology needs. The UV Sentry concept, envisions a system of systems of heterogeneous vehicles, sensors and weapons operating semi-autonomously to provide force protection capability. This project focused on the application of the UV Sentry concept to the counter piracy mission off east Africa. A basic Concept of Operations (CONOPS) was defined and focused on the protection of assets navigating the international shipping channel through the Gulf of Aden. A list of desired system attributes was established including adaptability, scalability, persistence, ability to operate with fewer people, reduced bandwidth and communications requirements, sparse supervisory control, an improved human-machine interface, more rapid response times, and over the horizon communications. This paper will discuss the concept, previous work done, and how the CINT team approached the problem.

INTRODUCTION

The United States Navy is a primary means of force projection throughout the world. Its ships serve to protect interests both home and abroad, but the threats faced and the roles required to be filled are evolving. One of the current challenges facing the US Navy is in keeping its fleet modern with fewer resources despite the accelerating pace of technology advancement. The UV Sentry force protection concept is designed to be more adaptable to changing threats, inexpensive to add capabilities, and a means of getting sailors and marines out of harm's way. It is a force multiplier; greatly increasing the capabilities of a small team of sailors from operating a single small craft to managing a fleet of small vehicles.

The implementation of a system of collaborative unmanned vehicles requires integrated solutions from many different disciplines. The exploration of the UV Sentry concept provided a unique opportunity to foster further collaboration between different Navy technology centers and provide young engineers and scientists the chance to work in a multidisciplinary team spanning the country. This year's effort had members from the Naval Surface Warfare Center, Carderock Division (NSWCCD) in West Bethesda, Maryland, the Naval Undersea Warfare Center in Newport, Rhode Island (NUWC-Newport), and the SPAWAR Systems Center, Pacific (SSC-Pacific) in San Diego, California.

This paper describes application of the UV Sentry concept to an anti-piracy mission off the coast of Somalia. Tasks were separated and assigned based upon the expertise of each center. The team members from NSWCCD worked on a USV design. The members at NUWC looked at means of autonomous, collaborative decision making. The efforts at SSC-Pacific were focused on C4ISR aspects, Human Machine Interface (HMI), and detection and classification.

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BACKGROUND

UV Sentry

UV Sentry is a concept that uses a system of systems of heterogeneous vehicles, sensors and weapons operating semi-autonomously to provide a force protection capability. Originally envisioned as a component of the defensive systems surrounding a sea base, the flexibility of the approach lends itself to large number of missions (Fetsch, Mailey, & Wallace, 2007).

CONCEPT DESCRIPTION

The UV Sentry system of systems of heterogeneous vehicles, sensors and weapons is best described as an integrated team of various unmanned vehicles and human operators collaborating to complete a mission. Such a system increases capability through coordinated actions of its member agents instead of attempting to engineer all necessary capabilities into a single platform. This concept has been successfully demonstrated with homogeneous vehicles specifically designed to work as a team but a team of heterogeneous vehicles has yet to be fielded. Despite this, a team of multiple types of unmanned vehicles is well within the feasible design space for deployments in non-adversarial environments, performing missions such as cooperative exploration and mapping of a previously unknown environment.

The goal of cooperative autonomy is to create synergy in the system prior to operator involvement. Synergy can be manifested in several ways. The first is through data fusion. This key enabler for cooperative autonomy increases the situational awareness of each vehicle, providing sensor data from additional perspectives to increase the fidelity of the internal model of the environment. A challenge of automated data fusion is determining which data need to be shared and how to present it. Once a system for creating and updating a shared situational model is established, opportunities abound for improving the performance of individual agents inside the system. For example, consider an Unmanned Surface Vehicle (USV) operating in a channel with numerous other craft. Given the mission to navigate through the channel, the USV must plan a path through the channel while avoiding all other craft and obstacles that exist. Current practice requires that the USV estimate its current position and the position of all other entities in the channel through sensors or preloaded information already located onboard. In a collaborative system, such as a USV and a small Unmanned Aerial Vehicle (UAV) working together to accomplish the same task, the position of the USV in the channel and its relative position and heading relative to the rest of the traffic in the channel could be quickly determined from an aerial point of view. This not only simplifies route planning, but would also identify any additional obstacles that are hidden from the sensor onboard the USV.

UV Sentry is an autonomous system in which agents communicate over a network, fuse data, and assist the human operators in directing the unmanned agents. It is specifically intended as a flexible architecture created to facilitate the operation of cooperative unmanned assets in theatre, capable of working with a variety of systems which may be appropriate for the current mission.

NSWCCD INNOVATION CENTER

The UV Sentry concept was developed and first explored as a NSWCCD Innovation Center project in 2005 (in collaboration with SSC Pacific). The results of that work were published through the Association for Unmanned Vehicle Systems International (AUVSI) in 2007 by Fetsch, Mailey, and Wallace. The original charter of the innovation center team was:

"Develop a concept of operations for a system of unmanned systems that will serve within Sea Shield as sentries to sense and identify current and projected surface and subsurface threats to Sea Base assets; and design the corresponding FORCEnet Services Infrastructure-based architecture and suite of unmanned vehicles."

The charter excluded air threats intentionally to narrow the team's focus. Additionally, the innovation center team chose to further narrow their focus to only defensive capabilities. However, as noted in their report, the nature of

the system allows for its augmentation to handle both air threats and offensive missions.

The primary results of the Innovation Center project were sets of concepts of operation (CONOPS) for different defensive missions, a list of technical capability gaps needing to be bridged, and a proposed path forward in the development of the system.

FURTHER CONCEPT DEVELOPMENT

After the conclusion of the Innovation Center Project, development of the UV Sentry concept continued under ONR funding. This work identified several missions to which the concept would add capability (Table 1). (Fetsch, Mailey, & Wallace, 2007)

Table 1: UV Sentry: Potential Navy Applications

Maritime Facility Protection: UV Sentry Value Added: Persistent, long endurance, asset-limited surveillance and tracking
Counter Drug Operations: UV Sentry Value Added: Persistent, long endurance, wide-area surveillance and tracking
Maritime Security/ Anti-Piracy UV Sentry Value Added: Persistent, long endurance, wide-area surveillance and warning
Maritime Domain Awareness UV Sentry Value Added: Persistent ISR, automated data fusion, autonomous mission planning and task allocation

During this phase of the project, the UV Sentry CONOPs for particular missions were further developed. Also, a set of critical technical enablers was identified that required further development prior to the realization of the UV Sentry concept (Table 2).

Table 2: UV Sentry Critical Enablers

Critical Technical Enablers

- Cooperative Autonomy
- Multi-foci data fusion
- Human-Computer Interface
- Supervisory Control
- Automated Threat Discernment
- Automated Launch, Recovery and Sustainment of Vehicles

Center for Innovative Naval Technologies (CINT)

The further exploration of the UV Sentry concept was selected as the pilot project for the Office of Naval Research (ONR) sponsored Center for Innovative Naval Technologies. CINT is intended to foster cooperative ventures among the US Navy's research laboratories and technology centers. Leveraging the already existing Naval Research Enterprise Intern Program (NREIP), young engineers and scientists can be recruited and organized in interdisciplinary teams spanning these Navy facilities across the country. The dispersion of these teams has several benefits including fostering interdisciplinary collaboration among the incoming generation of Navy engineers and scientists, increased project complexity and breadth, improved access to subject matter experts, and fostering working relationships between laboratories in an era facing challenges requiring innovative, interdisciplinary solutions. The CINT team for the UV Sentry project consisted of members residing at three different labs, NSWCCD, NUWC-Newport, and SSC-Pacific.

STUDY OBEJCTIVES

The project had two overarching objectives: (1) further explore the UV Sentry concept by applying it to a new mission and reexamining technology gaps; and (2), to provide a pilot CINT project, fostering cooperation between Navy centers and young engineers and scientists through a multidisciplinary project.

CINT Pilot Study Objectives

There were several objectives for the CINT pilot study. In addition to fostering interdisciplinary, cross-Warfare Center teams and providing young engineers and scientists opportunities to work on complex problems, the pilot study had the additional goal of establishing a model from which future CINT efforts could draw.

UV Sentry Objectives

The general technical goal of the CINT project was to advance the Navy's ability to operate large numbers of heterogeneous unmanned vehicles. This goal was broken down into a set

of questions and topics aligned with the expertise available at each of the three centers.

PLATFORM OBJECTIVES

The team members based at NSWCCD were given the lead on physical platform development. In this case, that took on the form of designing a USV capable of meeting the needs of the system in an anti-piracy scenario. The design needed to balance overall system cost, individual platform performance, and overall system coverage. During the design process, the team was directed to aggressively take advantage of the unmanned nature of the system when possible in order to see what capabilities could be achieved in a small craft when it doesn't need to accommodate human operators.

AUTONOMY OBJECTIVES

Work at NUWC and SSC-Pacific explored different aspects of autonomy. Their combined work was aimed at identifying enabling technology and methods for the autonomous, decentralized operation of multiple, heterogeneous unmanned vehicles. These efforts were focused on the areas of real-time tasking, machine learning, and autonomous target identification and classification.

COMMUNICATION OBJECTIVES

Communication amongst agents is necessary for them to collaborate. Therefore SSC-Pacific addressed the objective to identify requirement drivers for the communication system needs in a distributed system of unmanned vehicles.

HUMAN-MACHINE INTERACTION OBJECTIVES

It is necessary to understand the operator needs when asked to fulfill a supervisory role in a highly autonomous system. Two team members at SSC-Pacific examined the needs for interfacing between the operators and the unmanned systems in UV Sentry and the implications related to increasing the level of autonomy in system.

METHODOLOGY

Overall CINT Methodology

Prior to the arrival of the NREIP Interns, the mentors and sponsors for the project met to establish the team's goals for the summer. This also allowed for the assignment of topics to each team member that complimented each other.

During their ten week internships, the CINT team worked in separated teams according to the aspect of the overall system they were investigating. The entire team met and discussed their progress weekly utilizing webinars. These regular meetings kept all members apprised of the decisions being made at other centers and provided an open discussion forum for addressing issues. This allowed each team member enough freedom to effectively explore their part of the problem and allowed others the chance to benefit from their findings.

The intern projects culminated in a final meeting which was hosted by NSWCCD in the Washington, D.C area, where the team members presented the results of their work to each other in person. Additional members of the community attended and provided comments.

Center Specific Methodologies

Although the specific approaches employed during the investigation of the UV Sentry concept varied from focus area to focus area, all followed the same general pattern: identify a system need, postulate solutions, and evaluate those solutions while considering their total system impact. The team members looking at platform requirements worked on an actual concept design, using an iterative process to refine vehicle requirements and the platform specific CONOPS to arrive at a set of vehicles characteristics necessary to incorporate into their design. The team members looking at autonomy developed simulations to provide rudimentary proofs of concept for identified solutions. The remaining members, those looking at communication and the human-machine interface focused on the evaluation of existing systems to identify their strengths and short comings as applied to a system incorporating autonomous collaboration.

CONOPS DEVELOPMENT

The Maritime Security / Anti-Piracy mission was selected for further examination in the CINT project. It is a mission that currently has a great deal of attention and there is a large amount of publicly available information. A scenario was developed to apply UV Sentry, and CONOPS were determined for the systems based upon that scenario.

Anti-Piracy Scenario: Gulf of Aden

The CINT team was presented with the challenge of applying the UV Sentry system to an Anti-Piracy mission in the Gulf of Aden (Figure 1). In 2010, piracy incidents in and around the Gulf of Aden and the East coast of Somalia accounted for roughly half of the total reported attacks worldwide (IMO, 2010).That is an attack happening on average, every 40 hours in an area larger than the territorial waters off the Eastern Seaboard of the United States.

Figure 1: Gulf of Aden and Somalia
Source: *MaritimeSecurity.com*

The CINT team chose to focus on a 1000 nm strip extending from the West end of the Gulf of Aden and along an Internationally Recommended Transit Corridor (IRTC) into the East Arabian Sea (Figure 2). The IRTC through the Gulf of Aden is a 12nm wide strip consisting of two, 5 nm wide transit corridors with a 2nm wide buffer zone between them.

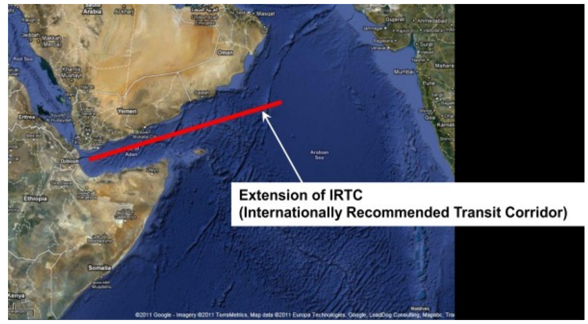


Figure 2: Area of Operations

This area coincides with the highest concentration of pirate attacks in recent years (**Error! Reference source not found.**). The high volume of traffic through this area, 33,000 vessels a year, presents the local pirates an ample number of potential targets in a concentrated area. By concentrating the scenario on the IRTC, the team was able to concentrate on a more tractable problem while maintaining the potential for having a significant impact on maritime security in the area.

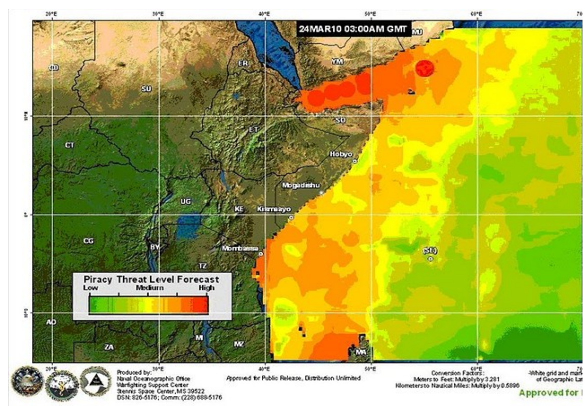


Figure 3: March 2010 Predicted Piracy Threat Levels

The pirates operating in this area are particularly difficult to detect or predict because they rarely use their own vessels when they attack vessels traveling through the area. They will often hijack local fishing boats and skiffs, use them to attack a vessel, and then abandon them immediately after the attack, regardless of the outcome. In addition to the difficulty of detecting a pirate vessel, defending against pirate attacks has become increasingly difficult. A typical tactic used in pirate attacks is launching several skiffs from a mother ship and attacking the target vessel from several directions at once (Figure 4). These swarm

tactics make it more difficult for the targeted vessel to prevent the pirates from boarding.

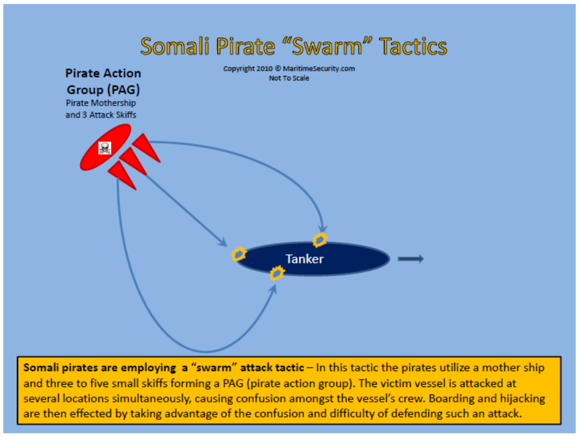


Figure 4: Pirate Tactics
Source: *MaritimeSecurity.com*

Typically, there are about 15 minutes between the initial detection of a pirate group by the ship to be attacked and the start of an attack. The goal of the UV Sentry system is to detect, intercept, and deter a pirate action group from attacking a vessel travelling through the IRTC. Under current circumstances a response of 15 minutes or less is required; however, the expectation is that with the increased situational awareness that the UV Sentry system will bring to bear, a longer response time would be acceptable. For the purposes of this effort, the maximum acceptable response time was set at 60 minutes.

System Level CONOPS and Requirements

The mission requires coordinating multiple vehicles over a 1,000 nm strip of sea, with incidents requiring intervention occurring roughly once every 2 days and a relatively short response time available to intercept a threat once located. In order to defend against a highly flexible and unpredictable adversary, the UV Sentry system needs to leverage the unique properties of each of the different platforms available to it: UAVs providing aerial surveillance of large swaths of the IRTC and surrounding waters, Unmanned Underwater Vehicles (UUV's) providing covert surveillance of known pirate harbors and other known threat sources, and USVs capable of holding station for long amounts of time and quickly responding to threats to successfully discourage the attack (Figure 5). The response would likely be in conjunction with manned forces.

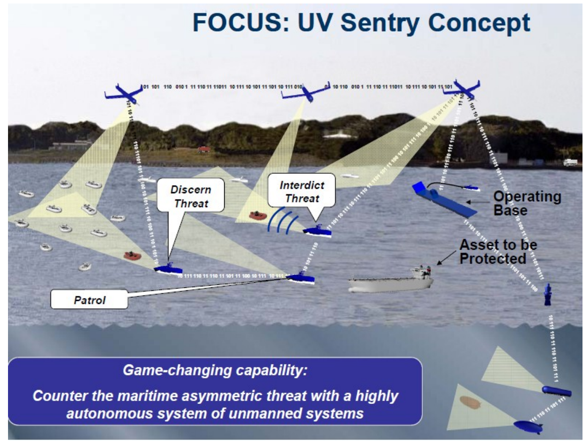


Figure 5: UV Sentry Concept Depiction

The system and its components need to be capable of operating at varying levels of autonomy depending upon the task. It is envisioned that the vehicles in the system would operate autonomously until they detected a threat, at which point the operation of vehicles would become increasingly less autonomous as the situation moved from detection to interdiction.

TOPICAL RESULTS

The results from the CINT study on the UV Sentry concept are presented in the following sections, by subject area.

Platform CONOPS and Design Results

Based upon the overall CONOPS for the UV Sentry, Anti-Piracy system, the NSWCCD team developed a set of platform specific CONOPS and requirements to fill the mission needs.

REQUIREMENTS AND CONOPS DEVELOPMENT

In order to provide coverage for the 1000 nm long shipping corridor without utilizing an infeasible number of vehicles, the USV CONOPS and requirements examined the balance between platform capability and number of systems deployed. The number of USVs deployed along the route drives several requirements in addition to vehicle speed. For instance: as more vehicles are placed along the route, the area of responsibility for each vehicle

shrinks. This in turns reduces the expected distance that a vehicle needs to travel each day, which reduces the amount of fuel that each USV would need to carry to remain on station for a fixed number of days. This could in turn allow for the downsizing of each USV, however, the vehicles need to survive in a seaway and be large enough to effectively deter a pirate attack. Analyses of this set of tradeoffs and others like it were used to develop a concept of operations for the USV (Figure 6).

The combination of this set of CONOPS and the environmental conditions in the Gulf of Aden translates into a set of operational requirements. In particular, the USVs must have a top speed of 40kts, be fully operable in sea state 4, survive in sea state 7, station keep in a surface current of at least 3kts, and sufficiently mitigate slamming loads to protect onboard equipment.

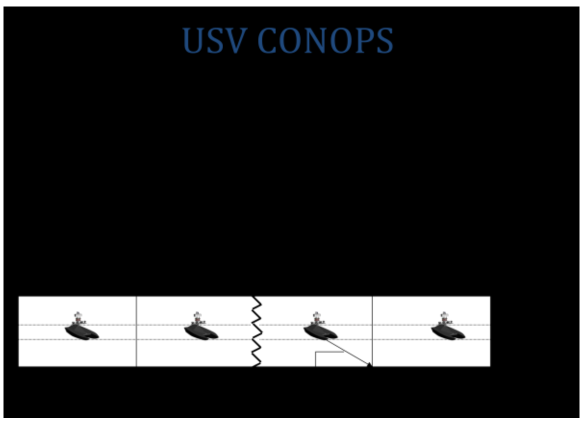


Figure 6: USV CONOPS

USV PLATFORM DESIGN

The driving requirement in the platform design was the need for mitigating slamming loads while sprinting in rough seas. In order to meet this requirement, a hydrofoil assisted catamaran (HySuCat) hullform was selected for the USV (Figure 7) (Hoppe, 1995). This hullform uses fixed foils for additional capability in rough seas and has been proven off the southern coast of South Africa with favorable seakeeping at speed in high sea states.

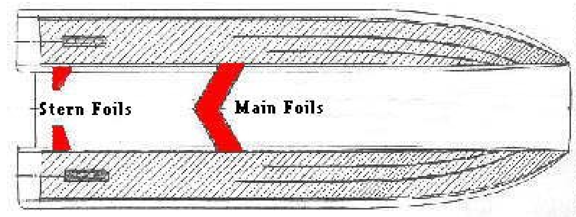


Figure 7: HySuCat Hullform

The UV Sentry HySuCat design provides a large, relatively stable, platform and a payload capacity capable of carrying the necessary sensor and weapons payloads (Figure 8). It is expected to be capable of the desired sprint speed of 40 kts with approximately 750 kW of power and adequately mitigate slamming loads while at speed. The USV carries a variety of sensors and includes provisions for a set of nonlethal weapons for use in deterring pirates. The nonlethal weapons that could be installed aboard could include devices such as water cannons, long range acoustic devices, and boat traps.

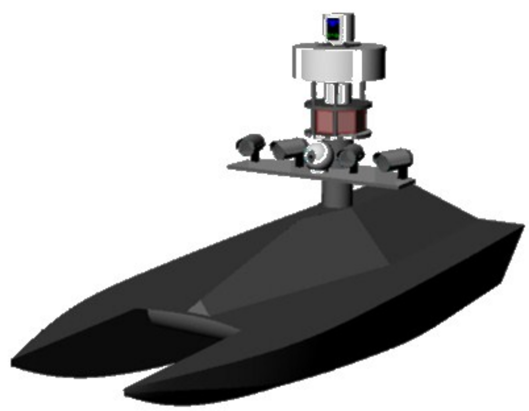


Figure 8: UV Sentry HySuCat concept.

Autonomy Research

Research was divided into three general thrusts, group or collaborative autonomy, machine learning, and autonomous threat perception.

GROUP AUTONOMY

The UV Sentry concept uses autonomous collaboration while maintaining physical platform flexibility. This requires an adaptive system capable of intelligently assigning tasks to its individual agents based upon their capability to complete the assignment. The CINT team

members at NUWC decided upon a combination of applied game theory and market based decision making to make autonomous group decisions when selecting an asset to perform a given mission. Market based decision making determines courses of action through auctions. When a task needs to be completed, agents in the system make bids based upon their ability to complete the mission. The agent with the most attractive bid is selected to perform the mission. The scheme explored for use in the UV Sentry concept relies on individual agents to run auctions. If a member of the system discovers a task which needs completion, it would then ask for bids from available nearby agents, select one of the auction bidders, and pass authority for that action to the auction winner.

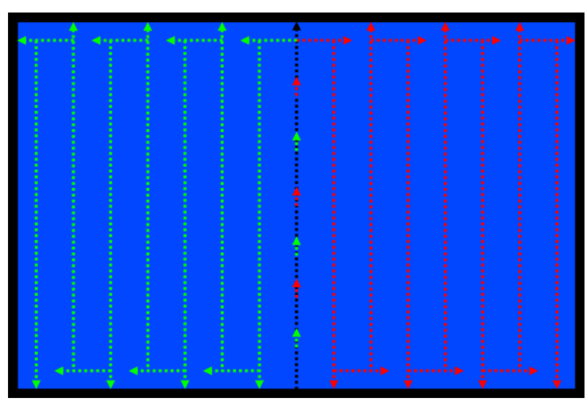
Members of the CINT team at NUWC created a proof of concept simulation using NUWC's in house simulation environment. They successfully coordinated a group of simple agents using the market based scheme. While the simulation was limited to the protection of a single high value asset with limited pirate activity, the basic concepts demonstrated are scalable with more work required to determine the correct set of equations to evaluate the capability of an agent to complete a mission.

MACHINE LEARNING

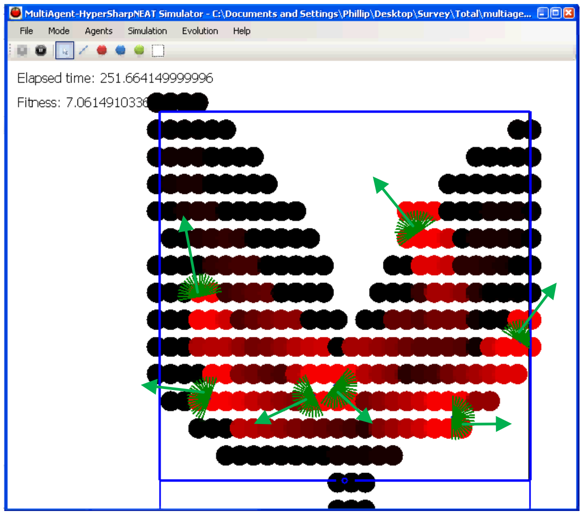
The issue addressed with machine learning is adaptability. When discussing a hard coded system questions arise about changing circumstances. How will the system cope with changing strategies on the part of the adversary? How will the system know how to properly incorporate multiple agents into its engagement and search strategies? The answer, at least in part, is by learning. The CINT team explored evolutionary learning techniques for teaching the system and its agents' behaviors.

Evolutionary learning techniques can be summarized as computer simulations of Darwin's "survival of the fittest theory". The process starts by populating the solution set with random guesses to the given problem. The members of the solution set are then evaluated by some objective function which assigns each of them a numeric fitness representing the strength of that particular solution. The set of guesses is then sorted by fitness and the weaker half of the solutions is removed. Then the population is refilled by a new set of guesses which use the stronger half of the previous generation as their starting points. This new population is then evaluated again, and the process repeats this loop of evaluate, sort, cull, and guess until it finds a solution with an acceptable level of fitness, reaches a preset number of maximum generations, or is stopped by the experimenter. At the end of the process, the algorithm has hopefully found some interesting solutions to the problem at hand.

The CINT team developed two scenarios to demonstrate tactical level agent coordination learned through evolutionary algorithms. The first was based upon detecting threats passing through an area and the second on maintaining protection coverage for multiple assets passing through a zone. In both cases, the algorithms produced well adapted solutions to the problem. In the detection case, the process started with a basic scripted search pattern and developed an apparently random search pattern in which each agent independently chooses its routes based upon a set of rules learned via the evolutionary process (Figure 9). The protection coverage example returned results which intuitively followed clusters of assets while tending to leave isolated assets to fend for themselves (Figure 10). While this may not be the best use of the agents available to the system, it is promising that the algorithm produced a predictable result given the fitness function used to create the solution.



(a) Scripted Search Pattern



(b) Learned Search Behavior
Figure 9: Search Pattern Comparison

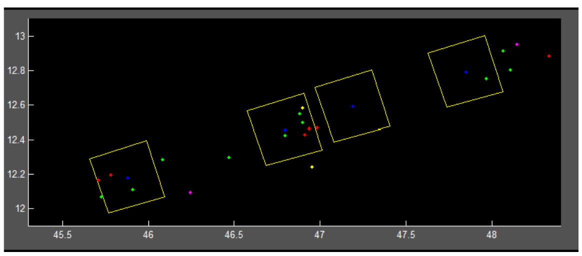


Figure 10: Optimized Asset Protection Coverage

The application of machine learning to the UV Sentry system requires the application of layered learning. Layered learning is a technique that decomposes the task down into separate layers and uses learning algorithms tailored to the needs of each layer (Stone & Veloso, 2000). UV Sentry is at its heart a monolithic multi-agent system comprising heterogeneous groups of homogeneous agents acting in a noisy, real-time, cooperative, and adversarial environment. The potential state space of this system is staggering; it includes the internal states of all of the agents, sensory input from satellite feeds, radar arrays, navigational information feeds, etc. To attempt learn a monolithic control mapping this state space to a set of actions for all of the agents is currently intractable and probably never will be. In fact to handle this system manually would require a well trained team of people with many different skills. That being said, the application of the principles of layered learning to this intractable problem break it down into manageable chucks that machine learning algorithms are capable of handling (Table 3). Some obvious layers in the UV Sentry system include the classification of pirates, the planning and scheduling of patrols, and the reactive controls of the individual UxV's.

Table 3: Principles of Layered Learning

Principle 1: A mapping directly from inputs to outputs is not tractably learnable. This will usually be the case when the state space is large, continuous, noisy, contains hidden states, etc. Layered learning instead uses a bottom up decomposition to incrementally learn a solution from low level tasks to high level strategic behaviors
Principle 2: The layers of the system are a function of the domain to be learned. The layers are defined a priori by the machine learning opportunities in the domain. However, it could be possible to combine layered learning with an algorithm that learns abstraction levels.
Principle 3: Machine learning is central to the layered learning paradigm to exploit data to train and/or adapt the system. Learning is done at each layer, and can be done off-line or on-line. The type of learning is also dependent on the subtask being learned.
Principle 4: The key aspect of layered learning is that the learning at each layer affects the next layer in the chain. A learned sub-task can affect the next layer in three ways; (1) by providing a portion of the behavior to be learned (2) defining the features that are learned (3) pruning the output set.

AUTOMATED THREAT PERCEPTION

The work discussed thus far has relied on the assumption that if a pirate vessel is in range of sensors on a vehicle, it can be detected with a relatively high rate of success. The last question posed to the CINT members working on autonomy was how do you determine if a contact is a pirate or not? Their answer was to adopt currently existing algorithms used for satellite image analysis for UAV use. In particular the Rapid Image Exploitation

Resource (RAPIER) Ship Detection System developed at SSC Pacific (SSC-Pacific, 2011).

RAPIER is a framework for processing satellite imagery. It has a modular design, allowing for new algorithms to be incorporated into its existing framework. It already handles a large range of data sources such as Synthetic Aperture Radar (SAR), Electro- Optical (EO), Multispectral, Infrared, etc. RAPIER has already been developed to include a suite of algorithms to automatically detect ships, mask land, detect and remove clouds, analyze background textures, remove glint and noise, and detect anomalies (Figure 11).

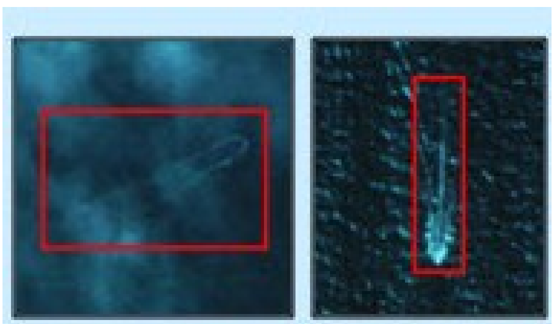


Figure 11: Advanced Algorithms Detect Ships behind Clouds and in Rough Seas

The RAPIER program is highly accurate but this accuracy comes at a price, requiring detailed images and large amounts of processing power. In order to utilize a detection suite like RAPIER one of three things needs to happen: the computation resources required needs to be reduced, the computational power at the sensor needs to be increased, or the communications systems need to be able to deliver the data to a location with sufficient computational power. These options define the trade space the UV Sentry system needs to explore.

Communication Systems

The communication system for the UV Sentry system needs to be both flexible and secure. With the system spread out over large areas this is difficult to achieve without tying up a large number of vehicles to serve as communication gateways. The suggested solution is to use an ad hoc network which changes its architecture based upon the required bandwidth. When the bandwidth requirements are relatively low, a few high altitude UAVs could be used as gateways to facilitate communication throughout the entire system (Figure 12). This has several benefits including reducing the number of required gateways, alleviating some multipath issues and facilitating long distance communications for USVs and UUVs.

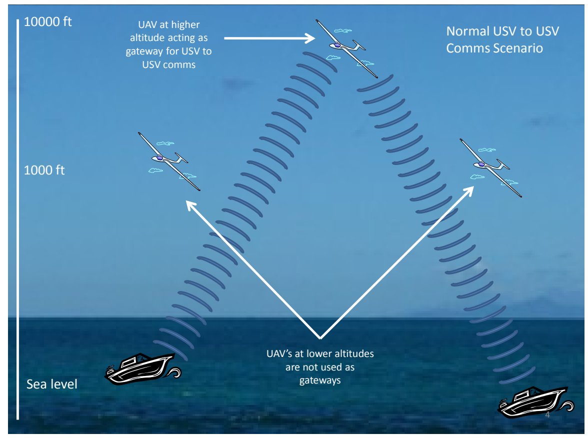


Figure 12: Low Bandwidth Network Concept

The second concept would be used when a high bandwidth transmission such as streaming video is required. For these cases all of the UAVs between the start and ending points of the transmission would serve as gateways (Figure 13). While this ties up more vehicles for data transmission it permits much higher bit rates allowing for long distance video transfer.

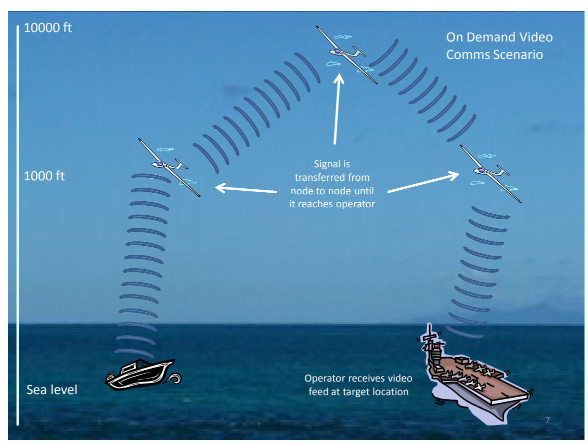
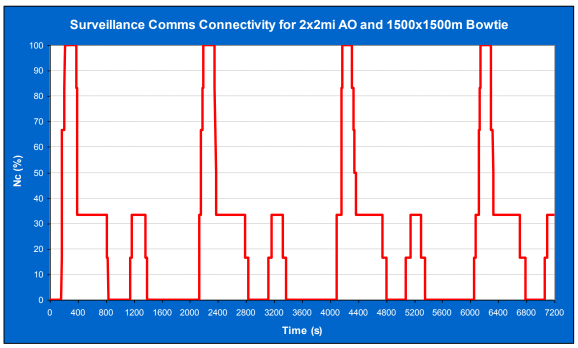


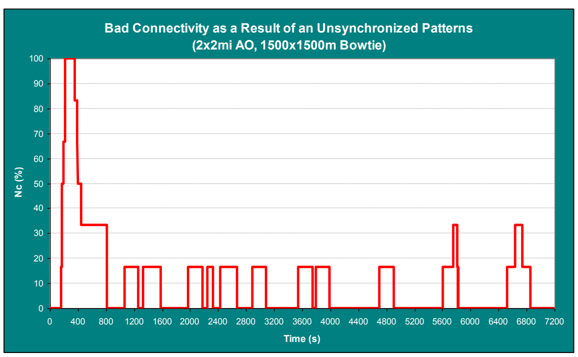
Figure 13: On Demand Video Network Scheme

Both of these concepts rely on constant connectivity between network gateways. Maintaining this connectivity is relatively simple for UAVs; however, one can imagine situations where a UAV would not be present to facilitate the communication between USVs or UUVs. In

these situations the amount of area that the vehicles would be capable of providing coverage to would be limited by their need for communication. In situations where the vehicles needed to only periodically communicate with each other it is possible to cover more area without increasing the number of agents. If this is done, it will be important to choose appropriate patrol patterns to minimize the effects that unsynchronized vehicle movements have on the connectivity of the group (Figure 14).



(a)



(b)

Figure 14: (a) Synchronized Vehicle Connectivity, (b) Unsynchronized Vehicle Connectivity

Human-Machine Interactions

A relatively large body of work exists on creating collaborative autonomous systems. In most cases, the systems are preprogrammed with set of behaviors. While this approach works well for developing and testing group autonomy theories, it is not a viable solution for a deployed system. UV Sentry must be capable of human-in-the-loop collaboration. In other words, it needs to be capable of actively sending and receiving input to and from human operators. In addition, this needs to be done in a fashion conducive to improving operator performance not decreasing it.

HUMAN FACTORS IN AUTOMATION

The CINT project sought to identify a set of guiding principles for creating an autonomous system designed to work with the human operator. A literature search indicated that autonomous systems are often designed for "dull, dirty, or dangerous" missions and will often result in an increase in overall system performance (Galster, 2007). However, over-automation of a task can make the human's job even duller than before, decreasing the overall system performance (Parasuraman & Manzey, 2010). The challenge of creating a well-designed, automated system which requires human supervision or interaction is striking the right balance between automation and operator involvement.

Several studies have shown that a key part in establishing the proper balance between operator involvement and automation is the visual interface design (Crandall & Cummings, 2007; Johnson, 2000). In general, the following set of guidelines apply broadly to designing display interfaces for future supervisory control, and should be taken into consideration in future HCI work for UV Sentry (

Table 4).

Table 4: System Design Principles

• Focus on the users and their tasks, not the technology
• Consider function first, presentation later
• Conform to the users' view of the task
• Do not complicate the users' task
• Promote learning
• Deliver information, not just data
• Design for responsiveness
• Try it out on users, then fix it

(Johnson, 2000)

HUMAN-MACHINE INTERFACE

In large, complex systems such as UV Sentry, one of the largest challenges when designing the operator interface is communicating the right information at the right time. Keeping in mind

the design principles identified during the literature search, an initial concept of a potential user interface for the UV Sentry system was created (Figure 15).

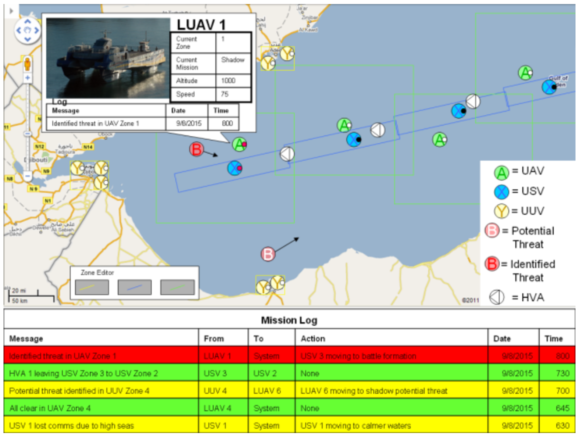


Figure 15: UV Sentry User Interface Live Map

The philosophy behind the user interface is to show the operator only what is critical at the time. For instance when no confirmed threats are present, the operator has two primary roles: monitoring the health of the vehicles and reviewing possible threats in the area of operations. During these times it would be detrimental to bombard the operator with interfaces for controlling group tactics for intercepting a pirate vessel unless they were specifically requested.

ANALYSIS OF RESULTS

CINT Pilot Study

The CINT Pilot Study worked well. Given the different geographic locations and the differing technical disciplines involved, communications amongst the team members was a critical factor in the success of the project. The project provided valuable experience to the students in this regard.

UV Sentry

A large number of the necessary pieces of UV Sentry are being actively developed for use in other programs; a few are already mature technologies. It seems reasonable to conclude that a large portion of the UV Sentry system may be possible in the next few years. The research areas in autonomy and communications provide a large portion of the necessary structure for a collaborative autonomy system. Automated perception enables the system to observe the world around it, thereby collecting data and building a state model from which decisions can be made. With market-based decision making, the system has the means to assess the capabilities of assets currently available to the system and assign them duties according to the perceived state of the area. Machine learning will allow the system to adapt over time to previously unforeseen circumstances. A well-designed human interface is essential for effective use of the UV Sentry system. Although not addressed in the CINT project, the language by which the agents in UV Sentry will communicate is a key aspect - there are several languages in use in academia for collaborative autonomy, including several which have been demonstrated in both experiments and simulations.

Finally, the viability of UV Sentry is dependent upon the future integration of all of the technical components, which will be a challenging endeavor.

CONCLUSIONS

The CINT UV Sentry project expanded the knowledge base surrounding the UV Sentry and served as the pilot study that future CINT projects can draw upon The CINT team created a collaborative, multi-disciplinary environment. The weekly meetings provided students an opportunity to discuss their progress and findings, and to receive feedback on the implications of their design decisions from the other mentors

The investigations made into different aspects of the UV Sentry concept revealed that while most of the technology gaps identified by the original UV Sentry Innovation Center still exist, the gaps are closing.

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Cullen Sarles *is the principal author and he is an employee of the Center for Innovation in Ship Design at Naval Surface Warfare Center – Carderock Division. He holds a B.S. in Naval Architecture and Marine Engineering from Webb Institute and is interested in unmanned systems. He is currently exploring the supervisory control of multiple unmanned systems.*

Alexandria Byrd

Ronald Duarte *received a BS in Computer Engineering from University of Rhode Island (May 2011). He is currently pursuing an MS in Computer Science and an MS in Electrical Engineering at the University of Rhode Island.*

Dr. Karl von Ellenrieder

Daniel Gorelik

Mark Groden

Robert Gutzwiller *is currently a PhD student at Colorado State University, where he earned his M.S. in cognitive psychology. His main research interests are in individual differences in applied cognition, and situation awareness in the context of automation and human-computer interactions.*

Davis Knox

Greg Koch

Jeremy Payne

John Reeder

Phillip Verbancsics

Virginia Wang

Dr. Robert A. Brizzolara *is a Program Officer at the Office of Naval Research. He manages science and technology programs in the area of small combatant craft, both manned and unmanned, including autonomous control for unmanned surface vehicles.*